X-641-69-238

PREPRINT

NASA TM X-63581

THE COSMIC GAMMA-RAY SPECTRUM FROM SECONDARY PARTICLE PRODUCTION IN COSMIC-RAY INTERACTIONS

F. W. STECKER

JUNE 1969

GSFC

GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND

X-614-69-238
Preprint

THE COSMIC GAMMA-RAY SPECTRUM FROM SECONDARY PARTICLE PRODUCTION IN COSMIC-RAY INTERACTIONS

F. W. Stecker

June 1969

Theoretical Studies Branch
NASA Goddard Space Flight Center
Greenbelt, Maryland

PRECEDING PAGE BLANK NOT FILMED.

TABLE OF CONTENTS

PRECEDING PAGE BLANK NOT FILMED.

THE COSMIC GAMMA-RAY SPECTRUM FROM SECONDARY PARTICLE PRODUCTION IN COSMIC-RAY INTERACTIONS

ABSTRACT

The cosmic gamma-ray spectrum below 1 GeV arising from cosmic-ray p-p interactions is calculated. Its properties are determined by the properties of secondary neutral pion production occurring at accelerator energies. An "isobar-plus-fireball" model is chosen for numerical calculations in which the two dominant modes of neutral pion production at accelerator energies are the production of the $\Delta(1.238)$ isobar and one fireball. Each of these modes of production then yields a component to the total gamma-ray spectrum. The affect of α-p and p-α interactions on the cosmic gamma-ray spectrum is also calculated. The components are summed and the results are given in terms of both differential and integral gamma-ray energy spectra.

THE COSMIC GAMMA-RAY SPECTRUM FROM SECONDARY PARTICLE PRODUCTION IN COSMIC-RAY INTERACTIONS

I. INTRODUCTION

In previous work, the general formulas were derived for the calculation of the gamma-ray spectrum due to secondary particles produced in cosmic-ray interactions with atoms of the interstellar or intergalactic gas (Stecker, 1966). A calculation was then made of the gamma-ray spectrum from cosmic-ray interactions for gamma-ray energies greater than 1 GeV (Stecker, Tsuruta, and Fazio, 1968). It was pointed out that the gamma-rays arising from the decay of heavy baryon secondaries (hyperons and nucleon isobars) determine the characteristics of the gamma-ray spectrum at energies greater than 6 TeV.

This paper deals with the detailed calculation of the cosmic gamma-ray spectrum from secondary particle production with particular emphasis on the energy region below 1 GeV. This region is of particular interest at present because the recent detection of cosmic gamma-rays in the region has indicated the possibility of spectral measurements in the near future (Clark, Garmire and Kraushaar, 1968) and because spectral measurements in this region will allow us to determine whether secondary particle production or another process is of prime importance in the production of galactic gamma-rays (Stecker, 1969).

Several authors (Pollack and Fazio, 1963, Hayakawa, Okuda, Tanaka and Yamamoto, 1964, Ginzburg and Syrovatskii, 1964) have addressed themselves to this problem in the past. However, in this paper we present a more detailed calculation based on the results of recent accelerator experiments.

The general features of gamma-ray spectra resulting from neutral pion-decay should be kept in mind whenever a discussion of a particular result is desired. The general results will prove invaluable as a guide in discussing the results of the particular model used in the numerical calculations.

These features may be summarized as follows (Stecker, 1966):

A. If we plot the general gamma-ray spectrum from neutral pion decay on a logarithmic scale in E_γ, the resultant curve will be symmetrical about the line $\ln E_\gamma = \ln (m_\pi/2)$.

B. The spectrum will have its maximum value at the point $E_\gamma = m_\pi/2$.

C. Higher energy pions produce a broader spectrum than their low-energy counterparts. They produce the gamma rays at the high- and low-energy extremes of the spectrum.

A specific model will be chosen that will be used for numerical calculation of the gamma-ray spectrum below 1 GeV. This model is of necessity an over-simplification of the true physics of pion production, but it can be made to fit the present accelerator data to an extent that is adequate for our purposes. The model is of the "isobar-plus-fireball" type. The terms "isobar" and "fireball" are here loosely defined to characterize the main features of the model. The model assumes that at accelerator energies there exist two dominant modes of pion production. Thus we may speak of two pion components; there is the isobar component, which dominates pion production in collisions where the cosmic-ray protons have energies in the low GeV range, and there is the fireball component, which supplies the main bulk of pions for p-p collisions of initial energy greater than 5 GeV.

II. THE ISOBAR-PLUS-FIREBALL MODEL

In this model, we will assume that in collisions of accelerator energies all pions are produced in either of two ways.

A. Via intermediate production and decay of the $\Delta(1.238)$ nonstrange isobar. This isobar is assumed to carry momentum directly forward or backward in the center-of-momentum system (c.m.s.) of the collision with an equal probability. The assumption made here is very similar to the one made in Stecker, et. al. (1968) for the other isobars and hyperons discussed.

B. From the energy remaining available in the c.m.s. of the collision, a thermal pion "gas" is created where the pions are given an energy distribution which is very similar to a Maxwell-Boltzmann type distribution (Morrison, 1963). This phenomenon is sometimes referred to as a fireball in cosmic-ray research and will be referred to as a fireball here. Its conception dates back to some of Fermi's early research into the problem of pion production in cosmic-ray collisions (Fermi, 1951). Our low-energy fireball is assumed to be roughly at rest with respect to the c.m.s. of the collision with its pions directed isotropically in this system. As an illustration, Figure 1 shows schematically the situation resulting from a TeV (10^3 GeV) collision as pictured in previous work (Stecker, et. al., 1968). The large difference in the behavior of the mesons and baryons emanating from the collision leads to the results obtained for the high-energy gamma-ray spectrum described in that paper.

The situation for low-energy collisions is not that simple, as is shown in Figure 2. As is indicated, it is much harder to distinguish between the two modes of pion production because of the similarity in the momenta involved. There is no longer the large disparity in c.m.s. momenta of the previous situation.

Indeed, we may even conceptually fuse the two components and envision all the created pions together as having an elongated c.m.s. momentum distribution whose anisotropy is a function of collision energy. A simple model of this type has been used by Hayakawa, Okuda, Tanaka, and Yamamoto (1964) in their calculations of the cosmic gamma-ray spectrum. However, the two-component model presented here utilizes the more detailed results of more recent accelerator experiments. Among the most striking of these results is the complete dominance of the $\Delta(1.238)$ production mode in collisions where $E_p < 3$ GeV (Muirhead, 1965 p. 666). Indeed, even for collisions below the threshold for production of the mass peak at 1.238 GeV, there is evidence that this resonance (whose mass distribution extends below 1.238 GeV) affects the pion energy distribution (Focardi, Saporetti, Bertolini, Grigoletto, Peruzzo, Santangelo, and Gialanella, 1965). We will assume here that below 3.16 GeV, all pion production occurs through the intermediate $\Delta(1.238)$ resonance. This hypothesis is in agreement with the observation that at about 0.6-GeV proton kinetic energy, the neutral pion distribution is isotropic, since in this energy range the isobar enhancement would be formed at rest in the c.m.s. The model is also in agreement with the observation of an increasing asymmetry in pion momentum toward the forward and backward directions as E_p increases, since at higher energies the isobars tend to carry more and more momentum in the forward and backward directions.

III. CALCULATION OF THE GAMMA-RAY SPECTRUM FROM THE ISOBAR PION COMPONENT

We are now ready to specify the parameters needed for the numerical calculation of the gamma-ray spectrum from the isobar pion component, hereafter referred to as the i-process component. For our model we need to specify

A. the energy distribution of the isobar in the c.m.s.

B. the angular distribution of the isobar in the c.m.s.

C. the energy distribution of the decay pions in the BARS (baryon-isobar rest system).

D. the angular distribution of the decay pions in the BARS.

E. the cross section for production of the $\Delta(1.238)$ isobar as a function of initial proton energy.

In our model (Stecker, et. al., 1968) the isobars are assumed to decay isotropically in the baryon rest system (BARS). The energy distribution of the decay pions is obtained from the Breit-Wigner form of the isobar mass distribution. The isobar mass distribution is assumed to peak at $M_0^* = 1.238$ GeV and have a width of 0.1 GeV. The Breit-Wigner distribution is given by

$$\mathfrak{F}(M^*) = \frac{1}{\pi} \frac{\Gamma}{(M^* - M_0^*)^2 + \Gamma^2}. \tag{1}$$

We denote the pion energy in the BARS by the symbol μ. In terms of isobar mass, μ is then given by

$$\mu = \frac{M^{*2} + M_\pi^2 - M_p^2}{2M^*}. \tag{2}$$

The normalized distribution function for μ is related to the normalized Breit-Wigner mass distribution by the transformation

$$\mathfrak{F}(\mu) = \frac{\mathfrak{F}(M^*)}{d\mu/dM^*}, \tag{3}$$

which then yields

$$\mathfrak{F}(\mu) = \frac{\Gamma}{\pi}\left\{\left[\left(\mu + \sqrt{\mu^2 + (M_p^2 - M_\pi)^2} - M_0^*\right)^2 + \Gamma^2\right] \left[1 - \frac{\mu}{\mu + \sqrt{\mu^2 + M_p^2 - M_\pi^2}}\right]\right\}^{-1}. \tag{4}$$

Equation (4) was solved on the CDC 6400 computer as a check on an intermediate step in the complete numerical solution. The results are graphed in Figure 3 along with the BARS gamma-ray distribution resulting from this pion distribution and given by

$$\mathfrak{F}(E'_\gamma) \equiv \int_{E'_\gamma + M_\pi^2/4E'_\gamma}^{\infty} \frac{d\mu\, \mathfrak{F}(\mu)}{\sqrt{\mu^2 - M_\pi^2}} . \tag{5}$$

In the actual calculation of the gamma-ray spectrum, we must take into account the kinematic limits on the allowed pion energy. There is only a limited amount of energy available for pion production. In order to specify a maximum BARS pion energy, μ_{max}, we note that in the extreme case where all the c.m.s. energy of the collision is transformed into the mass of the resonance we find

$$M^*_{max} = (2\gamma_c - 1) M_p , \tag{6}$$

and thus we can define

$$\mu_{max} = \frac{M^{*2}_{max} + M_\pi^2 - M_p^2}{2M^*_{max}} \tag{7}$$

We must then renormalize the distribution function over μ so that its integral over the allowed energy region is equal to unity. We thus define a renormalizing weighting factor

$$w_{rn} \equiv \left[\int_{m_\pi}^{\mu_{max}(E_p)} d\mu\, \mathfrak{F}(\mu) \right]^{-1} , \tag{8}$$

which multiplies the distribution $\mathfrak{F}(\mu)$.

We specify in our model, as before, that the isobars carry momentum either directly forward or directly backward in the c.m.s. (Morrison, 1963). We further assume that the low-energy i-process produces pions through the two-stage decay

$$p + p \to p + \Delta^{+}(1.238)$$
$$\qquad\qquad \hookrightarrow p + \pi^{0}$$
$$\qquad\qquad\qquad \hookrightarrow 2\gamma . \tag{9}$$

Let E_c be the total energy of the collision in the c.m.s., i.e.

$$E_c = 2M_p \gamma_c . \tag{10}$$

Furthermore, let us designate the energy of the isobar and proton in the c.m.s. system of the collision by E_{ci} and E_{cp}, respectively. Then

$$E_{ci} = \frac{E_c^2 + M^{*2} - M_p^2}{2E_c} . \tag{11}$$

The energy of the forwardly and backwardly produced isobars in the laboratory system are then

$$E_f = \gamma_c (E_{ci} + \beta_c p_{ci}), \tag{12}$$

and

$$E_b = \gamma_c (E_{ci} - \beta_c p_{ci}), \tag{13}$$

with

$$p_{ci} = \sqrt{E_{ci}^2 - M^{*2}} . \tag{14}$$

We may therefore write

$$\sigma(E_i ; E_p) = \frac{\sigma_i(E_p)}{2} [\delta(E_i - E_f) + \delta(E_i - E_b)] . \tag{15}$$

Using the results of previous calculations (Stecker, et al., 1968), it now follows that the gamma-ray spectrum from the $\Delta(1.238)$ i-process is given by the relation

$$I_i(E_\gamma) = \frac{\langle nL \rangle}{2} \int dE_p \, I(E_p) \, w_{rn}(E_p) \int dE_i \left(\frac{M^*}{\sqrt{E_i^2 - M^{*2}}} \right) \sigma(E_i; E_p) R_i$$

$$\int_{L(E_\gamma, E_i)}^{U(E_\gamma, E_i)} \frac{dE'_\gamma}{E'_\gamma} \int_{E'_\gamma + M_\pi^2/4E'_\gamma}^{\mu_{max}(E_p)} d\mu \frac{\mathfrak{Z}(\mu)}{\sqrt{\mu^2 - M_\pi^2}}, \tag{16}$$

where w_{rn} is defined by equation (8), μ_{max} is defined by equation (7), E'_γ is the gamma-ray energy in the BARS, $R_i = 2/3$ is the branching ratio for the neutral pion decay mode of the $\Delta(1.238)$ isobar,

$$U(E_\gamma, E_i) = \frac{E_\gamma}{\gamma_i (1 - \beta_i)}, \tag{17}$$

and

$$L(E_\gamma, E_i) = \frac{E_\gamma}{\gamma_i (1 + \beta_i)}. \tag{18}$$

All the integrations in equation (16), except for the dE_p integration, were carried out numerically by Gaussian quadrature on a CDC 6400 computer. The integration over dE_p was carried out in the following manner:

The product $R_i \sigma_i(E_p)$ (in millibarns) was approximated by the discontinuous function. This function was taken to be a three-part power law of the form

$$
R \quad (E_p) = \begin{cases} 0 & \text{for} \quad E_p < 1.48 \text{ GeV} \\ 10^{-1} E_p^{6.7} & \text{for} \quad 1.48 < E_p < 1.88 \text{ GeV} \\ 6.9 & \text{for} \quad 1.88 < E_p < 3.16 \text{ GeV} \\ 69\, E_p^{-2} & \text{for} \quad 3.16 < E_p < 10 \text{ GeV}, \end{cases} \tag{19}
$$

with σ_i in mb.*

The differential cosmic-ray proton intensity is shown in Figure 4.

IV. CALCULATION OF THE GAMMA-RAY SPECTRUM FROM THE FIREBALL COMPONENT

We now calculate the gamma-ray spectrum produced by pions created in the c.m.s. of the collision. We will refer to these pions as the fireball component. (The use of the term here is restricted to our previous definition.) For the purpose of discussion, we define the f-process (as opposed to the i-process) as the following production and decay scheme:

$$
\begin{aligned}
p + p \rightarrow p + p + \; & F \\
& \hookrightarrow \zeta_\pm \pi^\pm + \zeta_0\, \pi^0 \\
& \qquad\qquad\quad \hookrightarrow 2\zeta_0 \gamma,
\end{aligned} \tag{20}
$$

where $\zeta_\pm$ and ζ_0 are the average numbers of charged and neutral pions, respectively (a function of initial proton energy), and F is the so-called fireball. By no means should F be regarded as a real particle; it is better to picture it as a bosonic nonparticle whose only properties are 1) a momentary possession of

---

*Such a cross section is an approximation which assumes complete dominance of the i-process for neutral pion production in collisions involving kinetic energies below 1 GeV but which maintains the observed E^{-2} energy dependence of the $\Delta(1.238)$ cross section in various channels for kinetic energies above 2 GeV (Muirhead, 1965, W. E. Ellis, D. J. Miller, T. W. Morris, R. S. Panvini and A. M. Thorndike, 1968, Phys. Rev. Letters 21, 697, P. L. Connolley, W. E. Ellis, P. V. C. Hongh, D. J. Miller, T. W. Morris, C. Onannes, R. S. Panvini and A. M. Thorndike, 1967, BNL internal report 11980.

the mass-energy of the created pions, and 2) a momentary occupation of the interaction volume centered at the center of momentum of the collision and therefore moving at β_c with respect to the laboratory system.

We assume that the fireball decays isotropically with a c.m.s. energy distribution which is roughly independent of energy. The justification for this assumption comes both from accelerator studies (Morrison, 1963; Fidecaro, Finocchiaro, Gatti, Giacomelli, Middelkoop, and Yamagata, 1962) and from studies of interactions of cosmic-rays in the atmosphere (Fowler and Perkins, 1964). Accelerator studies of p-p interactions for energies up to 30 GeV give a charged-pion transverse-momentum distribution that fits an empirical law of the form

$$f_\pi(p_\perp) \propto p_\perp \, e^{-2p_\perp/\langle p_\perp\rangle_\pi} \tag{21}$$

(Morrison, 1963). Studies at 300 GeV (Guseva, Dobrotin, Zelevinskaya, Kotelnikov, Lebedev, and Slavatinsky, 1961) fit this law very well. (There is only a change in normalization involved, indicating an increased multiplicity.) It has also been observed that $\langle p_\perp\rangle_\pi$ is roughly constant in p-p collisions involving energies of up to 10^4 GeV (Fowler and Perkins, 1964). If neutral pions also obey this law, we would expect that the resultant gamma rays would have a transverse-momentum distribution of the form

$$f_\gamma(p_\perp) \propto e^{-p_\perp/\langle p_\perp\rangle}, \tag{22}$$

with

$$\langle p_\perp\rangle_\gamma = \frac{1}{2} \langle p_\perp\rangle_\pi . \tag{23}$$

Data confirm this exponential distribution for $p_\perp > 0.1$ GeV in p-p collisions of energies up to 10^4 GeV (Fowler and Perkins, 1964). Accelerator experiments (Fidecaro, et. al., 1962) mesuring the gamma-ray spectrum from p-p interactions at 23.1 GeV have substantiated indications of an exponential distribution of neutral pions in the c.m.s. The data are well represented by an energy distribution function of the form

$$f(E_\gamma^{(c)}) \propto e^{-4E_\gamma^{(c)}}, \tag{24}$$

Thus, over a wide range of energies

$$f_\pi(p_\perp) \propto p_\perp \, e^{-2p_\perp/\langle p_\perp \rangle_\pi}. \tag{25}$$

The quantity $p_\perp$ is a relativistic invariant that is proportional to the c.m.s. momentum of the pion, and, therefore (relativistically) to its c.m.s. energy. Letting ξ stand for c.m.s. pion energy, we may therefore use the approximation

$$\mathfrak{Z}(\xi) \propto \xi \, e^{-2\xi/\langle\xi\rangle}. \tag{26}$$

Since $\langle\xi\rangle \simeq 0.5$, independent of energy for collisions involving energies up to 10^4 GeV, we find that

$$\mathfrak{Z}(\xi) = \frac{1}{Z} \xi \, e^{-4\xi}, \tag{27}$$

with the normalization constant Z defined by

$$Z = \int_{m_\pi}^{\mu_{max}(E_p)} d\xi \, \xi \, e^{-4\xi}, \tag{28}$$

so that

$$\int_{m_\pi}^{\mu_{max}(E_p)} d\xi \, \mathfrak{Z}(\xi) = 1. \tag{29}$$

Evidence for a two-component pion production model with the f-process component producing pions isotropically in the collision c.m.s. has been presented by Dekkers, Geibel, Mermod, Weber, Willitts, and Winter (1964). Their work indicates that the i-component yields a very large ratio of positive-to-negative pions. Thus, the negative pions arise principally through the f-process.

It is then found that at accelerator energies, most negative pions are produced isotropically in the c.m.s. (the remaining ones being consistent with a small contribution from $N^* \to N\,\pi\,\pi$ decays).

We have thus assumed that the i-process plus the f-process provide all the pions produced, i.e.,

$$\zeta_f\,\sigma_f = [\zeta(E_p)\,\sigma(E_p)]_{Total} - \sigma_i\,(E_p). \tag{30}$$

The function $[\zeta(E_p)\,\sigma(E_p)]_{Total}$ is shown in Figure 5.

A gamma ray of energy $E_\gamma^{(c)}$ in the c.m.s. may have any laboratory energy E_γ within the range

$$\gamma_c\,E_\gamma^{(c)}\,(1-\beta_c) \le E_\gamma \le \gamma_c\,E_\gamma^{(c)}\,(1+\beta_c). \tag{31}$$

Under our assumption of uniform c.m.s. pion emission for the f-process, there is a constant production probability,

$$f\,(E_\gamma;\,E_\gamma^{(c)}) = \frac{1}{2\gamma_c\,\beta_c\,E_\gamma^{(c)}}, \tag{32}$$

within this energy range. It follows from equation (31) that the integral over the source function with respect to $E_\gamma^{(c)}$ is bounded by the upper and lower limits U_F and L_F, respectively, where

$$U_F(E_p) = \frac{E_\gamma}{\gamma_c(1-\beta_c)} \tag{33}$$

and

$$L_F(E_p) = \frac{E_\gamma}{\gamma_c\,(1+\beta_c)}, \tag{34}$$

since only gamma rays within this c.m.s. energy range will produce gamma rays of laboratory energy E_γ.

Therefore, the complete formula for the gamma-ray spectrum arising from the f-process is

$$I_f(E_\gamma) = \frac{\langle nL \rangle}{2} \int dE_p \, \frac{\zeta_f(E_p)\, \sigma_f(E_p)\, I(E_p)}{\gamma_c(E_p)\, \beta_c(E_p)}$$

$$\times \int_{L_F(E_p)}^{U_F(E_p)} \frac{dE_\gamma^{(c)}}{E_\gamma^{(c)}} \int_{E_\gamma^{(c)} + m_\pi^2/4E_\gamma^{(c)}}^{\mu_{max}(E_p)} d\xi \, \frac{f(\xi)}{\sqrt{\xi^2 - m_\pi^2}} \, . \qquad (35)$$

The resulting f-process spectrum was obtained numerically, using the same methods previously described for the evaluation of the i-process spectrum. The results of the numerical integration are shown in Figure 6. Figure 6 also shows the total spectrum produced by summation of the i- and f-components. The integral spectrum is given in Figure 7.

V. COSMIC GAMMA-RAYS PRODUCED IN COSMIC-RAY p-α AND α-p INTERACTIONS

Up to this point, we have restricted ourselves to a discussion of cosmic gamma-ray production in cosmic-ray p-p interactions. The details of particle production in p-p interactions have been well studied in recent accelerator experiments. Such is not the case for interactions involving protons and helium nuclei. However, these interactions may be expected to provide a substantial contribution to the total gamma-ray production of roughly the same magnitude as the contribution from p-p interactions and therefore these interactions cannot be neglected.

Figure 5 shows the total cross section times multiplicity for neutral pion production in proton-helium interactions as a function of kinetic energy per nucleon. Below 1 GeV/nucleon kinetic energy, these cross sections have been determined experimentally (Prokoshkin and Tiapkin (1957a, b), Batson, Culwick, Klepp, and Riddiford (1959), and Kozodaev, Kalyukin, Sulyaev, Filippov, and Shcherbakov

(1960)). Below 1 GeV/nucleon kinetic energy, it has been found experimentally that neutral pion production procedes predominantly through the $\Delta(1.238)$ production channel, this manifested both by the angular distribution of the pions and the 2:1 ratio of neutral to positive pion production in p-n interactions (Prokoshkin and Tiapkin, 1957a). We have therefore made the assumptions that the same isobar-plus-fireball model used for p-p interactions is also valid for p-α and α-p interactions, that the i-process dominates below a total energy of 3.16 GeV/nucleon and that the energy dependences of the cross sections for the i-process and the f-process are the same for nucleon-nucleon collisions in all of these interactions (charge independence). For interactions involving kinetic energies greater than 1 GeV/nucleon, the cross section data was extrapolated by assuming that the energy dependence of the pion multiplicity has the same form for α-p and p-α interactions as for p-p interactions. We assume also that the cross section for $\Delta(1.238)$ production decreases with energy as E^{-2} as is the case for p-p interactions. The assumption is also made that the pions are produced primarily in interactions which simulate free nucleon-nucleon interactions (Batson, et. al. (1959)) but with shadowing corrections as given by Kozodaev, et. al. (1960).

The energy spectrum of cosmic-ray alpha particles at solar minimum is shown in Figure 4. These particles produce gamma-rays by interacting with the interstellar gas (primarily α-p interactions). To this contribution, we must add the contribution of cosmic-ray protons interacting with helium nuclei in the interstellar gas (p-α interactions). Interstellar helium is estimated to make up approximately 36% of the nucleons in the interstellar medium so that the ratio of helium nucleons to hydrogen nucleons is 0.57 (Allen, 1963).

The differential energy spectrum of cosmic gamma-rays from α-p and p-α interactions was calculated based on the intensities and cross sections given in Figures 4 and 5 respectively and on the assumptions given above. The results of this calculation, when added to the results of the p-p calculations, yield the total spectrum given in Figure 6. The total integral production spectrum is shown in Figure 7.

ACKNOWLEDGMENTS

Most of this work was carried out at Harvard College Observatory and the Smithsonian Astrophysical Observatory. The author would like to gratefully acknowledge and thank Dr. Giovanni Fazio for his suggestions and for many fruitful discussions.

FIGURE CAPTIONS

Figure 1 – A schematic representation of the distribution of secondary pions resulting from a nucleon-nucleon interaction in the TeV energy range.

Figure 2 – A schematic representation of the distribution of secondary pions resulting from a nucleon-nucleon interaction in the GeV energy range.

Figure 3 – The energy distribution function of pions in the BARS resulting from the decay of the $\Delta(1.238)$ isobar and the energy distribution function of gamma-rays in the BARS resulting from the decay of these pions.

Figure 4 – The differential cosmic-ray proton and alpha particle energy spectra.

Figure 5 – Cross section times multiplicity for neutral pion production. Data for p-p interactions as summarized by Muirhead (1965). Data for α-p interactions from Prokoshkin and Tiapkin (1957a, b), Batson, Culwick, Klepp, and Riddiford (1959), and Kozodaev, Kulyukin, Sulyaev, Filippov, and Shcherbakov (1960).

Figure 6 – The calculated differential production spectrum of gamma-rays produced in cosmic-ray interactions based on the isobar-plus-fireball model described in the text.

Figure 7 – Calculated integral production spectrum based on the results of Figure 6.

REFERENCES

Allen, C. W., 1963, Astrophysical Quantities 2nd ed., Althone Press, London.

Batson, A. P., Culwick, B. B., Klepp, H. B., and Riddiford, L., 1959, Proc. Roy. Soc. A, 251, 233.

Clark, G. W., Garmire, G. P., and Kraushaar, W. L., 1968, Astrophys. J. (Lett.) 153, L203.

Dekkers, D., Geibel, J. A., Mermod, R., Weber, G., Willitts, T. R., Winter, K., Jordan, B., Vivargent, M., King, N. M., and Wilson, E. J. N., 1965, Phys. Rev., 137, B962.

Fermi, E., 1951, Phys. Rev., 81, 683.

Fidecaro, M., Finocchiaro, G., Gatti, G., Giacomelli, G., Middelkoop, W. C., and Yamagata, T., 1962, Nuovo Cimento, 24, 73.

Focardi, S., Saporetti, F., Bertolini, E., Grigoletto, A., Peruzzo, L., Santangelo, R., and Gialanella, G., 1965, Nuovo Cimento, 39, 405.

Fowler, P. H., and Perkins, D. H., 1964, Proc. Roy. Soc., 278A, 401.

Ginzburg, V. L., and Syrovatskii, S. I., 1964, Sov. Phys. JETP 18, 245.

Guseva, V. V., Dobrotin, N., Zelevinskaya, N., Kotchnikov, K., Lebedev, A., and Slavatinsky, S., 1962, Proc. Intl. Union Pure Appl. Phys. Conf., Kyoto, 3, 375.

Hayakawa, S., Okuda, H., Tanaka, Y., and Yamamoto, Y., 1964, Prog. Theor. Phys. Suppl. (Japan), No. 30, 153.

Kozodaev, M. S., Kulyukin, M. M., Sulyaev, R. M., Filippov, A. I., and Shcherbakov, Yu. A., 1960, Sov. Phys. JETP 11, 511.

Morrison, D. R. O., 1963, CERN/TC/Physics 63-1.

Muirhead, H., 1965, The Physics of Elementary Particles, (New York Pergamon Press), p. 666.

Pollack, J. B., and Fazio, G. G., 1963, Phys. Rev. 131, 2684.

Prokoshkin, Iu. D., and Tiaplin, A. A., __________ 1957a, Sov. Phys. JETP 5, 618, __________ 1957b, Sov. Phys. JETP 6, 245.

Stecker, F. W., 1966, Smithsonian Ap. Obs. Spec. Rept., No. 220.

Stecker, F. W., 1969, Nature, 222, 865.

Stecker, F. W., Tsuruta, S., and Fazio, G. G., 1968, Ap. J., 151, 881.

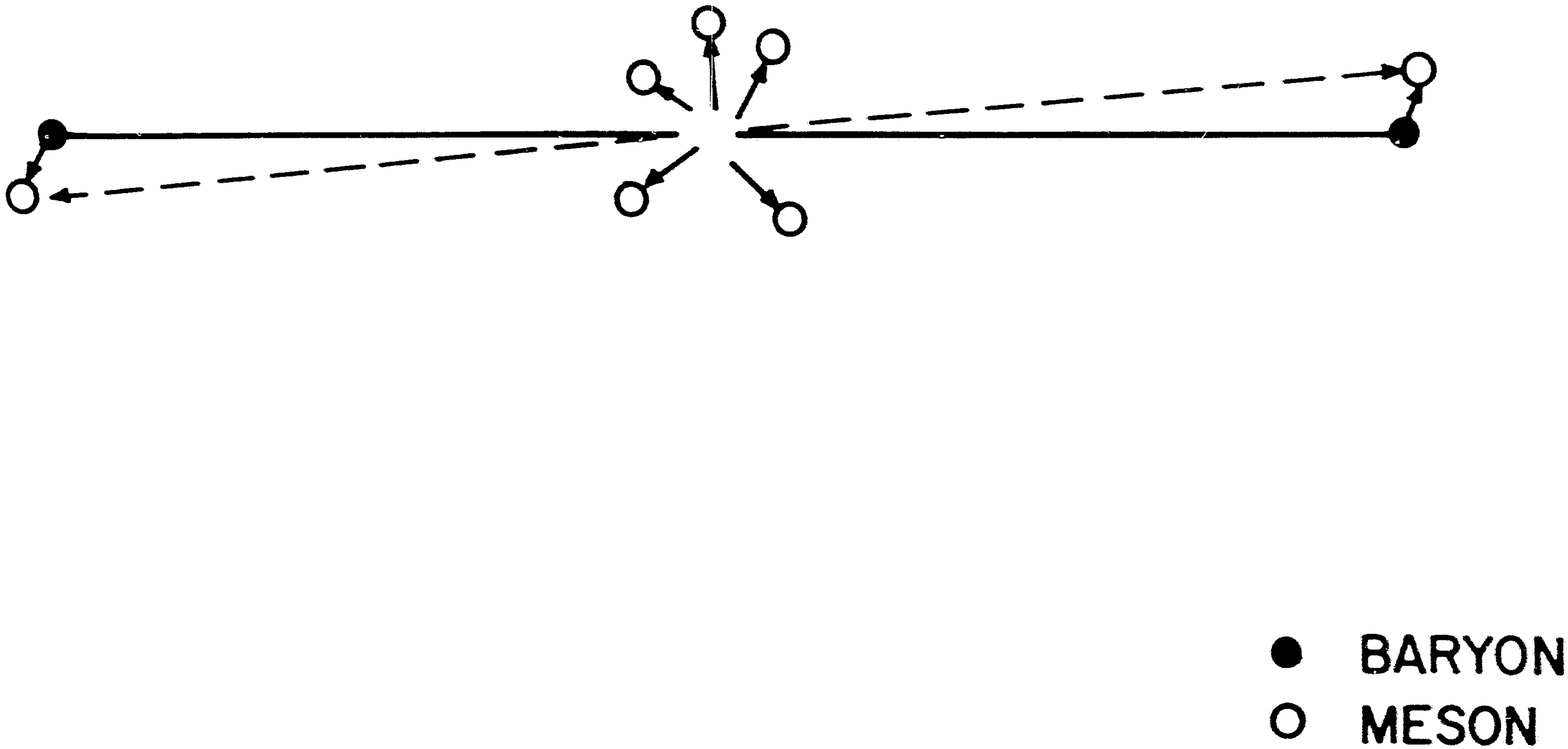

Figure 1—A schematic representation of the distribution of secondary pions resulting from a nucleon-nucleon interaction in the TeV energy range.

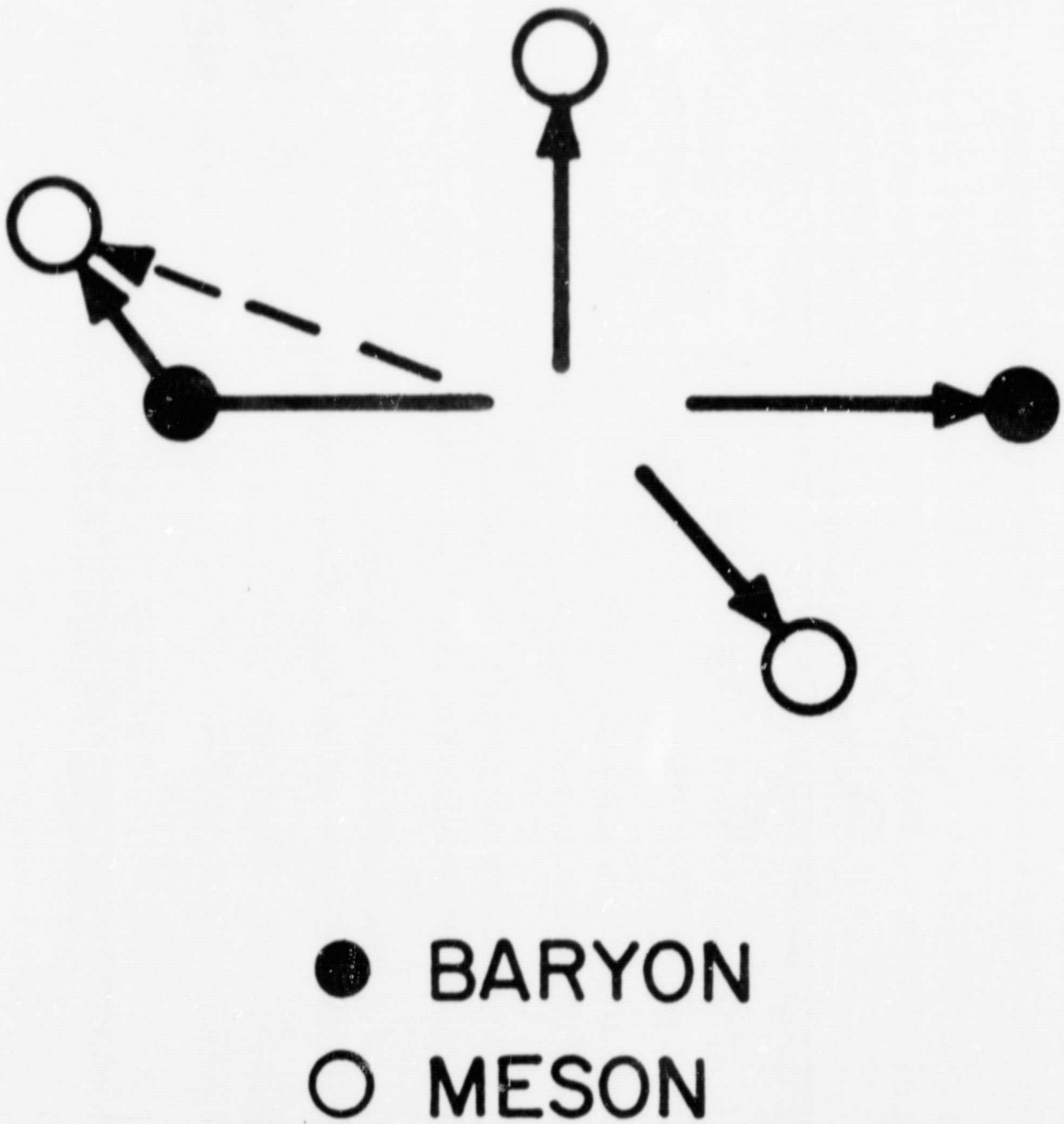

Figure 2—A schematic representation of the distribution of secondary pions resulting from a nucleon-nucleon interaction in the GeV energy range.

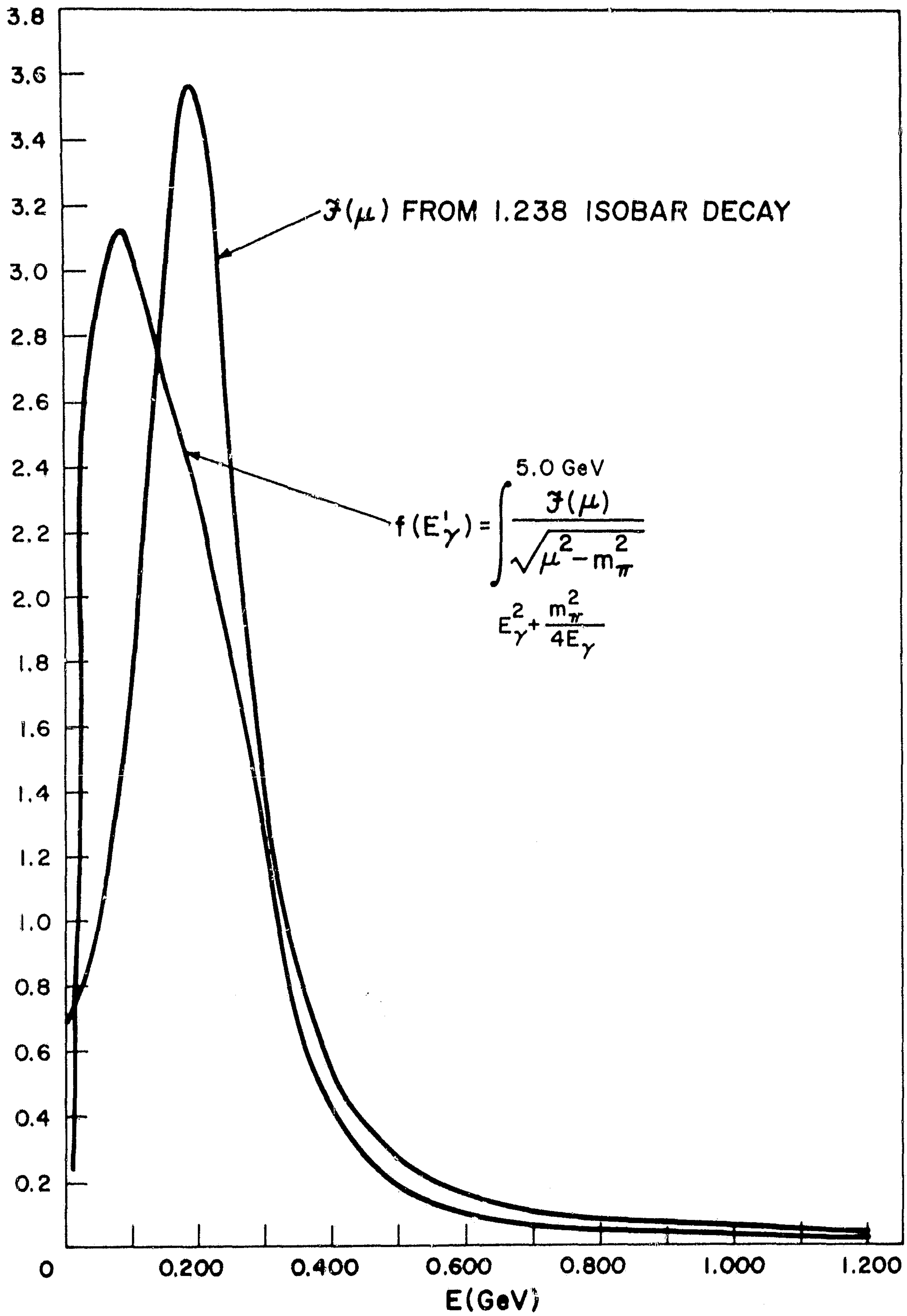

Figure 3–The energy distribution function of pions in the BARS resulting from the decay of the Δ(1.238) isobar and the energy distribution function of gamma-rays in the BARS resulting from the decay of these pions.

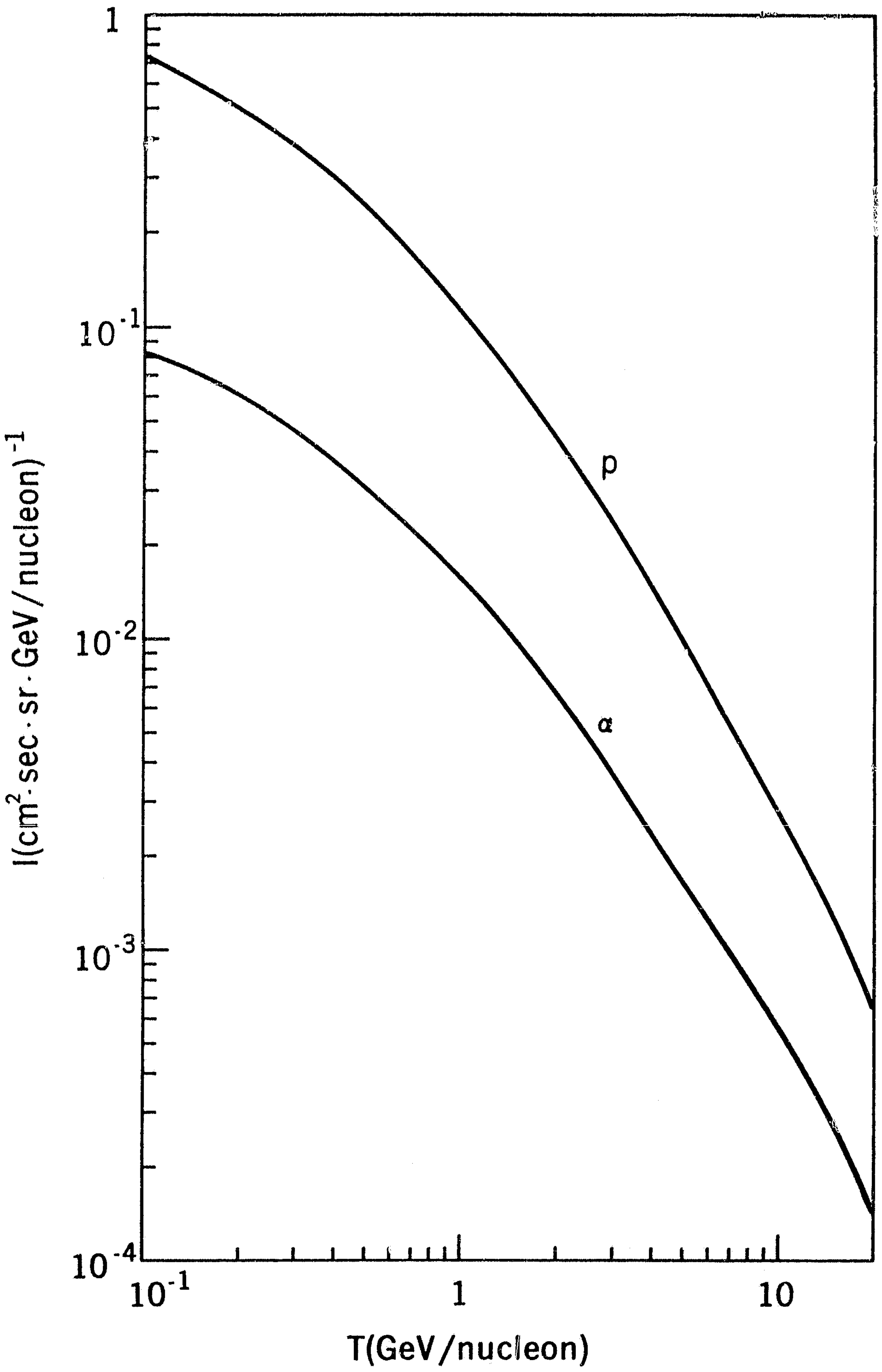

Figure 4—The differential cosmic-ray proton and alpha particle energy spectra.

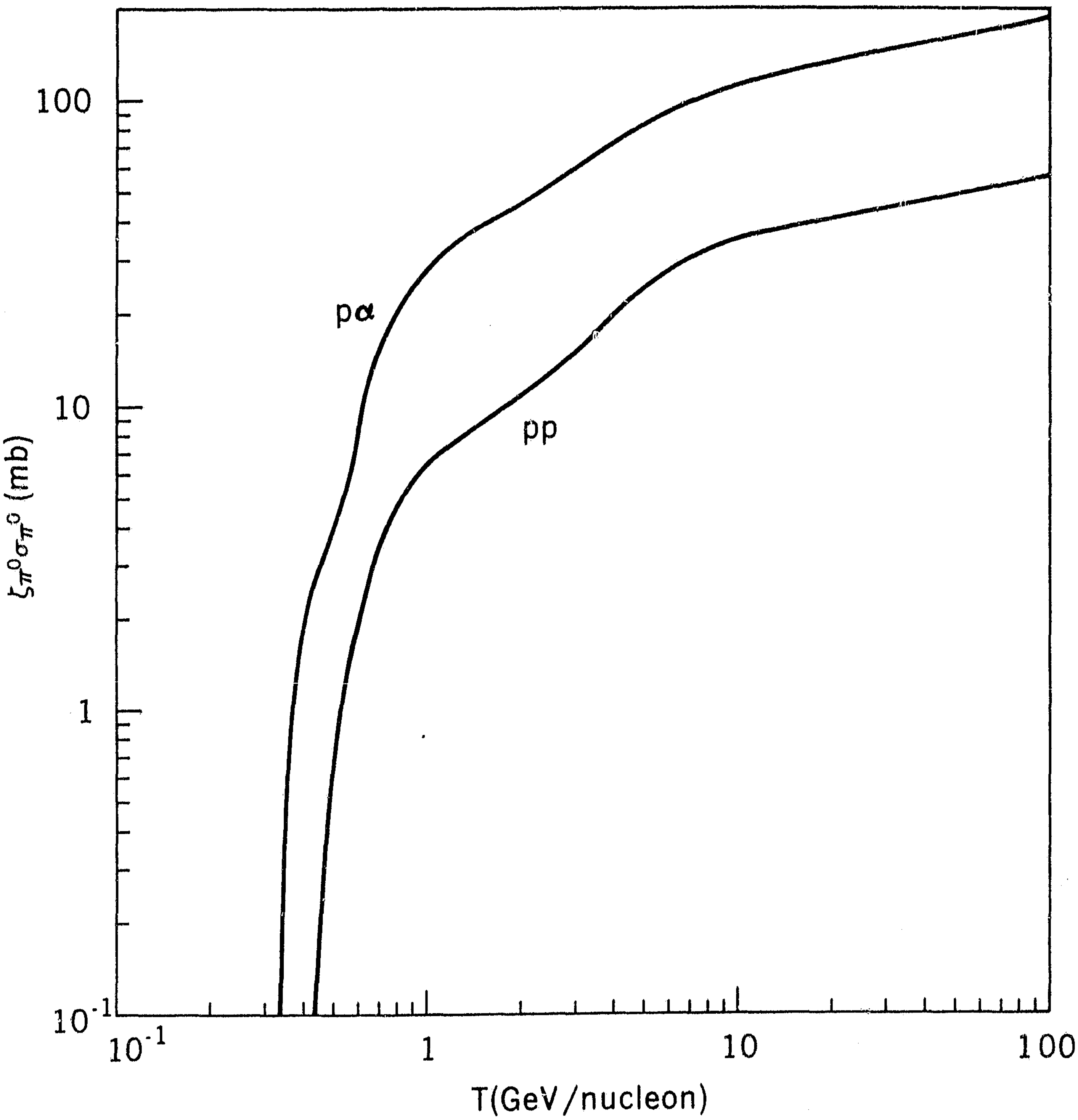

Figure 5–Cross section times multiplicity for neutral pion production. Data for p-p interactions as summarized by Muirhead (1965). Data for α-p interactions from Prokoshkin and Tiapkin (1957a, b), Batson, Culwick, Klepp, and Riddiford (1959), and Kozodaev, Kulyukin, Sulyaev, Filippov, and Shcherbakov (1960).

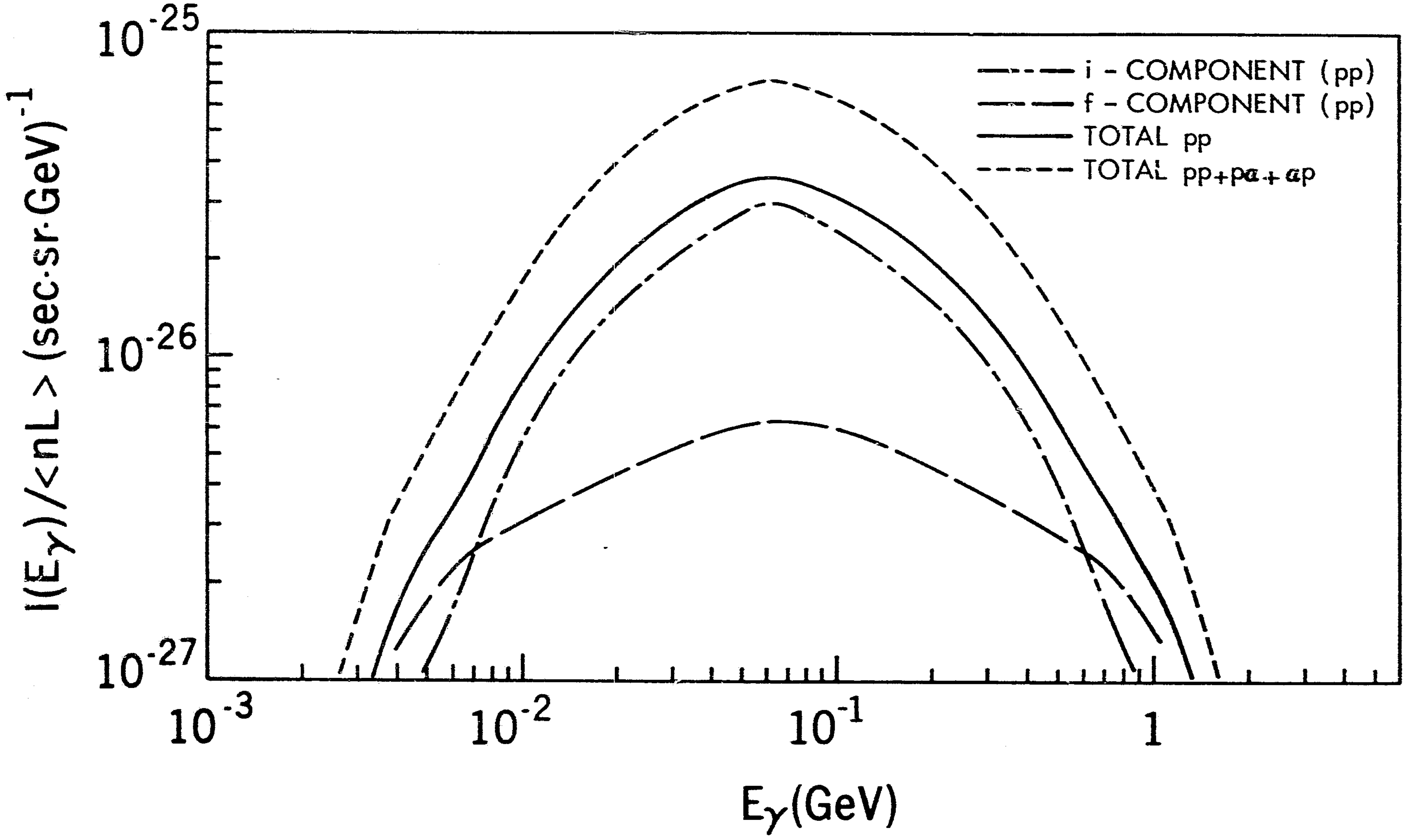

Figure 6—The calculated differential production spectrum of gamma-rays produced in cosmic-ray interactions based on the isobar-plus-fireball model described in the text.

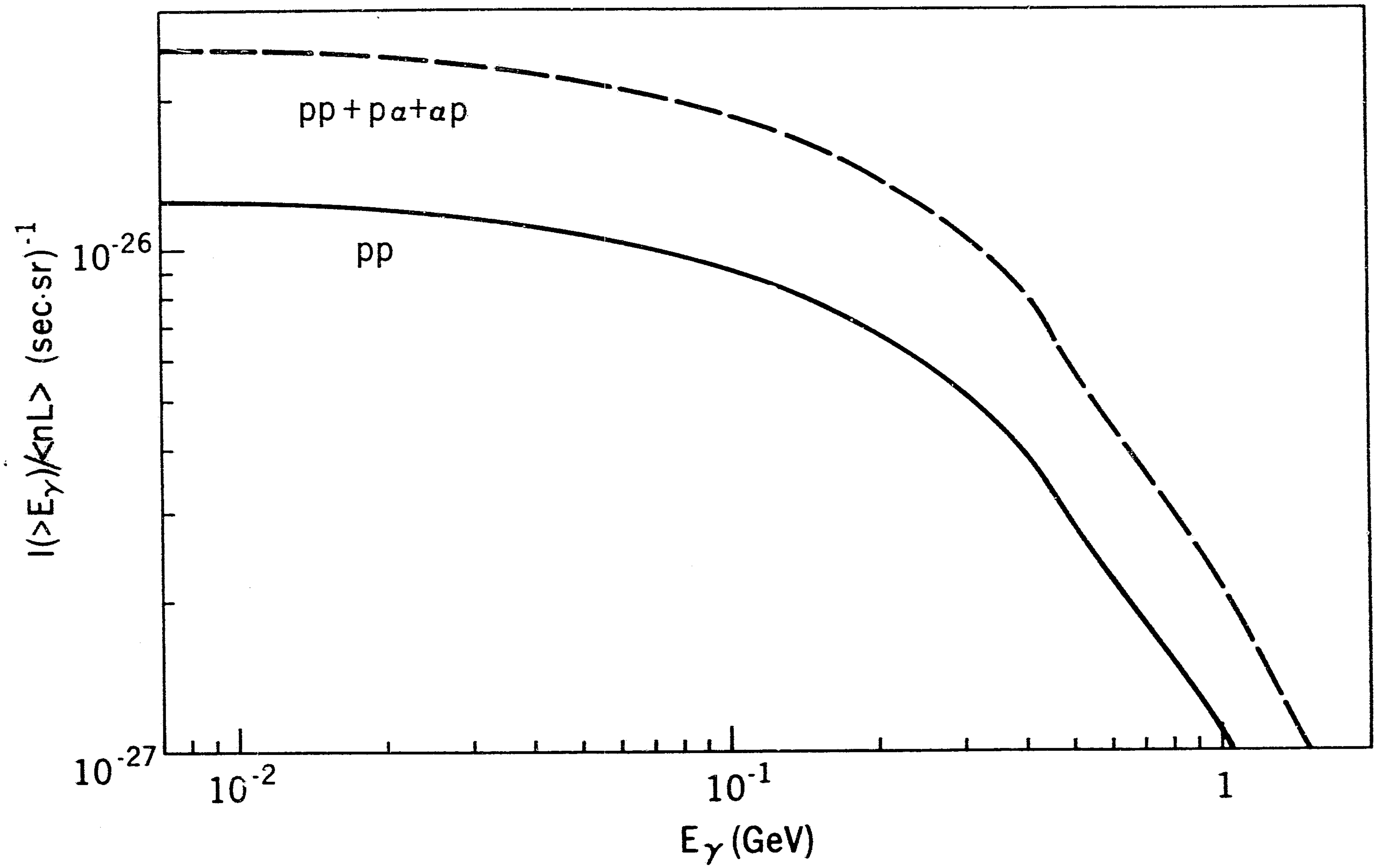

Figure 7—Calculated integral production spectrum based on the results of Figure 6.